20 Wheat[1]

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Wheat (*Triticum aestivum* L. and *T. turgidum* L. var. *durum*) is the world's major crop source of calories and protein (Thorne, 1977). It is grown over a wide range of precipitation and temperature conditions, mostly in the 25 to 50° lat range. Wheat production has expanded into the lower latitudes to less than 15° as a cool-season crop (Khalifa et al., 1977) and to about 60° lat in the Northern Hemisphere as a spring-planted, warm-season crop grown at the lower elevations.

Irrigation is widely practiced in some of the major production regions in the Northern Hemisphere and to only a limited extent in the Southern Hemisphere, primarily southeast Australia (Smith et al., 1983). Most of the wheat in the major production regions of India, Pakistan, and the People's Republic of China (PRC) is grown under irrigation. Irrigation has played a major part in the PRC becoming the world's number one wheat-producing country. In the USSR, the world's second largest producer, wheat is mostly grown under rain-fed conditions. The USA is the third largest producing country, and wheat is the third largest irrigated crop after corn (*Zea mays* L.) and alfalfa (*Medicago sativa* L.). Irrigated yields in 1984 averaged 4.6 Mg/ha (USDC, 1984). Wheat is principally a cool-season, temperate-zone crop. However, it is grown during the cool season at higher elevations in some tropical zone countries. The only major crop production regions where it is not grown are in the hot, low-lying tropics.

In India and Pakistan, wheat is usually grown during the dry season and irrigation is the major water source. It is also grown as an irrigated crop in the arid regions of Arizona, California, Washington, and Idaho and in the irrigated valleys of northwest Mexico. In semiarid regions such as the Pacific Northwest and Great Plains states, where wheat is widely grown as a dryland crop, it is also grown under limited irrigation in conjunction with seasonal rainfall. Supplemental or limited irrigation of wheat is also practiced in some semiarid regions of India and the Middle East.

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In 1979, irrigated wheat in India occupied 14.7 million ha, about two-thirds of the cultivated area (Sinha et al., 1985). In the USA, almost all of the irrigated wheat is grown in 17 western states, where, in 1984, it totaled 1.82 million of the 23.9 million ha (USDC, 1984). Wheat irrigation was widely dispersed in the Central and Southern Plains states and in the northwest and southwest states. Except for 67 000 ha in Montana, irrigation was relatively insignificant in the northern Plains states. The largest production area was in Texas (363 000 ha), followed by California and Kansas (290 000 ha each), Idaho (266 000 ha), and Washington (145 000 ha).

A U.S. Wheat Studies Delegation that visited the PRC in May 1976 reported that 80 to 85% of the wheat was irrigated (Johnson & Beemer, 1977). Wheat was being grown on 20% of the arable land, with production in all provinces, ranging from 18 to 50 °N lat. Wheat in the PRC has been stable in area since 1978 at 44 to 45 million ha (PRC, 1986). In 1978, national yields averaged 1.84 Mg/ha, and soil fertility was a major limitation to irrigated yields. From 1978 to 1984, fertilizer consumption for all crops increased from 9 to 18 Tg (Brown, 1986); and by 1984, national wheat yields averaged 2.97 Mg/ha (PRC, 1986). The increased yields were accomplished without further expansion in irrigated area.

I. GROWTH AND DEVELOPMENT

A. Vegetative-Reproductive

Extensive literature exists on the growth and development of the wheat plant. The Feekes scale of growth stages as reported by Large (1954) has been widely used in the USA, while in Europe, it has been largely replaced by the Zadoks decimal code (Zadoks et al., 1974; Tottman, 1987). Further developments in classification of growth and development were described by Haun (1973) and Klepper et al. (1982, 1984). A modern standard reference on development of wheat and barley is Kirby and Appleyard (1984). A simple but physiologically sound three-stage growth system, used in temperature studies of wheat by Warrington et al. (1977) and discussed by Eastin et al. (1983) and Evans and Wardlaw (1976), will be used in this review. Wheat growth and development physiology related to the three phases of vegetative, reproductive, and grain growth is described as follows:

GS1—Emergence to floral initiation (FI). Leaves and roots grow until the apex changes from initiating leaves to initiating the inflorescence as described in photographic sequence by Bonnet (1966) and George (1982). This period can be long for early planted winter wheat cultivars that require vernalization for FI or short for late fall- or spring-planted spring wheat cultivars that do not have a vernalization requirement.

GS2—Floral initiation to postanthesis beginning of grain growth. This is an exponential reproductive growth period in which green leaf

Area index (LAI) increases and peaks 2 to 3 wk before anthesis, root growth increases on a weight basis until anthesis, and the inflorescence grows and develops the potential grain numbers. Pollination occurs at anthesis, and grain growth begins. Culm growth continues only a few days after anthesis. Environmental stresses may severely limit potential grain numbers and yield potential.

GS3—Grain growth to physiological maturity. Grain growth begins and proceeds, following a few days lag after anthesis, as a linear process with time except for a few days at the beginning and end of the filling process. During grain growth, green LAI progressively declines, root growth continues at a reduced rate where conditions are favorable, and some previously stored assimilates are relocated to the grain. Environmental stresses primarily reduce yields by reducing the duration of grain filling and grain weight. Physiological maturity, in general, correlates with loss of head greenness and can be more specifically estimated by the water content of the grain as indicated by the absence of a wet endosperm surface when a kernel is pulled apart at the crease.

Some wheat genotypes require long photoperiods for floral development to anthesis, while others are photoperiod-neutral. Winter types require a chilling period (vernalization) for floral initiation, while spring types have little or no vernalization response. However, substantial variation occurs among both winter and spring types in vernalization requirement and photoperiod response. Spring types are late fall planted in the lower latitudes and spring planted in the higher latitudes where they cannot survive the cold temperatures.

The effects of environment on growing season duration of spring wheats are illustrated in Fig. 20–1 for locations in India with latitudes ranging from 11 to 32 °N (Sinha et al., 1985). The growing season duration to maturity of 100 to 150 d was associated with a range of irrigated grain yields from 1.6 to 5.0 Mg/ha, and yields and days to maturity were highly correlated. In these tests, relatively high irrigated yield levels of 4 to 5 Mg/ha from research plots were obtained only at locations where the latitudes exceeded 25 °, corresponding to about the southern boundary of the major production region in India. Increasing altitude reduces temperatures and increases length of growing season, thus increasing yields. In Zimbabwe, Cackett and Wall (1971) reported irrigated yields of 6.5 to 8.5 Mg/ha in the highveld and 4.0 to 5.5 Mg/ha in the lowveld, at elevations differing about 1100 m.

Wiegand and Cuellar (1981) determined from field plot studies at 26 °N lat that for each °C increase in mean air temperature during grain filling, duration of grain filling was shortened by 3.1 d and final kernel weight was reduced by 2.8 mg. The data by Wiegand and Cuellar (1981) compare with 2.8 d and 1.5 mg per kernel per °C from eight previous studies reported in the literature. In the low-latitude environments (below about 35 °N), spring wheat is late fall planted and matures in mid to late spring. The crop is grown

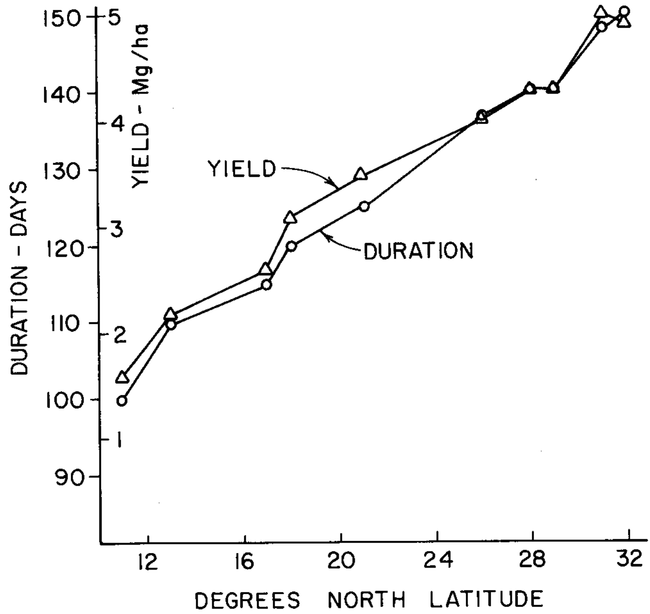

Fig. 20-1. Growing season duration of spring wheat and grain yield of irrigated wheat in India for locations having latitude ranging from 11 to 32 °N (adapted from Sinha et al., 1985).

during the cool season and escapes some of the adverse effects of increasing late spring temperatures.

At the higher latitudes, where spring wheat has insufficient cold tolerance for winter survival, spring planting is practiced and harvest occurs in late summer. In these climatic regions of long days and moderate air temperatures, solar radiation has a dominant climatic influence on yields. Under the long-day environment, improved cultivars produce high yields given adequate water, fertility, and good management. Fall-planted irrigated winter wheat is grown mostly in the central and western USA from about 32° to 44 °N lat, with production extending to 46 to 48 °N lat at the relatively low to moderate elevations of the Columbia Basin, the Palouse region of Washington, and north-central Montana.

Winter wheat cultivars planted in the USA in September or October mature from late May in central Texas to August in Washington. In the mid-latitude region of continental climate with relatively hot summers, winter wheat is better adapted than spring wheat and normally produces higher yields. Low temperature episodes can cause freeze damage when the wheat is not covered with snow. As winter wheat resumes growth in late winter and early spring, it loses cold conditioning, and low temperatures can cause death of green leaf area and damage to the elongating culm and developing apex (George, 1982). Later frost events can result in head sterility. Heavily fertilized irrigated wheat, with its lusher growth and higher N content, is more likely to be damaged by frost (Fischer, 1981a).

B. Roots

The root system of wheat was carefully observed and recorded by Weaver (1926), and root growth was received by MacKey (1973). Spring wheat cultivars commonly develop roots to about 1-m depth, while winter wheats, with their longer vegetative growth period, develop roots to about 1.5 m. In favorable rooting environments, winter wheat roots can develop to depths in excess of 3 m (Kmoch et al., 1957; Cholick et al., 1977). Studies involving semidwarf cultivars have shown no relationship between plant height and rooting depths or soil water depletion (Cholick et al., 1977, Holbrook & Welsh, 1980).

The root system terminology of seminal and nodal is used in this discussion. *Seminal roots*, three to seven in number, develop from primordia in the seed. Due to their early start, they dominate rooting during the seedling stage and continue a decreasing dominance until about mid-season, when nodal roots (crown or adventitious) become increasingly important (MacKey, 1973). *Nodal roots* develop from nodes in the crown in sequence as the main culm and tillers develop, with the earlier developed roots being longer and more branched than later ones. The *main culm roots* develop first and tend to dominate the nodal root system. Later-developing *tiller nodal roots* are short in length and senesce when tillers senesce.

Seminal roots are deeper, finer, have a higher order of branching than nodal roots, and tend to have a near-linear distribution with depth. They tend to have a direct downward orientation (Belford et al., 1987), remain active throughout the season, and provide the greater fraction of the roots in the lower profile; thus, their importance increases under conditions of major soil water deficits.

Nodal roots are exponentially distributed with depth; after about mid-season, they comprise the major weight of the root system in the upper profile. Klepper et al. (1984) reported that root length densities of 6 cm/cm^3 were common in surface soils, while densities of 1 cm/cm^3 were found at the 0.5- to 1.0-m depth. This distribution change with depth is associated mostly with changes in nodal root densities.

Nodal roots have an oblique outward development pattern that reorients in the downward direction, which increases the extent of lateral rooting. MacKey (1973) indicated that early developed nodal roots increased effectiveness in water and nutrient absorption compared with the later developing ones which are thicker, shorter, and less branched. He indicated that early development of nodal roots appears to have a restrictive effect on the growth of seminal roots, and the nodal root system tends to become dominant in rooting activity after about mid-season.

Nodal root growth normally begins about 25 to 30 d after plant emergence unless growth is prevented by cool temperatures. Dry surface soil at the crown can prevent the initial extension of nodal roots, and major surface soil drying during tillering can slow or prevent new nodal root growth from tiller nodes. For fall-planted wheat that emerges and grows during a dry season, irrigation may be essential for providing surface soil water to permit normal extension of nodal roots. In the southern High Plains, dry winters at Bushland, TX, have resulted in persistence of dry surface soil and delay in nodal root extension from November until the jointing irrigation in April. In contrast, the senior author has observed nodal roots in soil core samples to depths of 1.5 m by jointing in April. On this soil (Richfield clay loam; fine, montmorillonitic mesic family of Aridic Argiustolls) with a deep silt subsoil favorable for root development (1.25 Mg/m^3 bulk density), irrigated wheat depleted soil water to $<15\%$ available before yield reductions occurred (Musick et al., 1963). Early deep development of the nodal root system is believed to have contributed to the ability of the plants to deplete soil water from the lower profile.

Irrigation research in India has shown that crown (nodal) root initiation stage is the most critical for scheduling irrigation of late fall-planted spring wheat grown on sandy soils in environments where plants have a relatively short duration of vegetative growth. The crown root stage is critical in environments where significant water deficits can develop due to limited rooting and the water deficits are expressed through reduced vegetative growth (tillers, leaf area, and dry matter accumulation). Also, delayed irrigation in this environment fails to compensate for the lost growth in the relatively short growing season (Fischer, 1981b). Misra and Choudhary (1985) found a highly significant ($R^2 = 0.92$) curvilinear relationship between root density by weight and grain yield. Under dryland conditions, Black (1970b) found an association between nodal roots per plant and grain yields.

Gregory et al. (1978) have discussed the partitioning of plant assimilates between roots and tops under water deficit conditions. They indicated that during fall growth, the plant allocates about one-fourth of its dry weight accumulation to roots; the allocation to roots increases to about one-third during winters as cool temperatures limit vegetative growth; it rapidly declines during spring to about 0.09 at anthesis as developing leaves, culms, and the growing head become increasingly stronger sinks for assimilate. The root system reaches its maximum weight at anthesis. During grain filling, as older roots die and new root activity slows in the lower profile, partition of assimilates to roots is about 0.07. At harvest, the root system constitutes about 10% of the plant dry matter.

If severe late-season stress develops, the plant's investment of assimilates in developing a large early season root system may be detrimental to late-season soil water reserves and grain yield (Passioura, 1977). However, on irrigated land, the soil profile is normally fully wet to the potential rooting depth; a large and, thus, deeper root system may be effective in exploring additional water resources for plant use. This extensive profile wetting to lower depths may not be the case under dryland farming conditions with limited rainfall.

Death of tillers results in death of tiller nodal roots (Gregory et al., 1978). However, failure of tiller nodal roots to develop may not be the cause for failure of tiller development or senescence of developed tillers. In the absence of nodal roots providing nutrients and water uptake to tillers, death of late-developed tillers is more likely to be related to reduced assimilate from shading, water stress, or low competitive partitioning from the main plant during rapid growth.

C. Yield and Yield Components

1. Yield

Wheat yields in the USA increased by 32% during a 20-yr period through 1980 (Schmidt, 1984). The genetic yield potential of experimental lines compared with long-term check cultivars increased from 25 to 46% during the 20-yr period. About half of the increase in wheat yields was attributed to breeding for improved cultivars. In addition to improved cultivars, increased yields can be attributed to improved irrigation, fertilizer use, and cultural management. In the semiarid climate of the southern High Plains, the annual rate of irrigated wheat yield increase from 1968 to 1986 was double that of dryland wheat (58 vs. 26 kg/ha per yr, J.T. Musick, 1987, unpublished data). The importance of irrigation in increasing wheat yields is further emphasized by the contribution to the "green revolution" of expanded irrigation of wheat in India (4.8 million ha in 1966 compared with 14.7 million ha in 1979) (Sinha et al., 1985).

Irrigated wheat yields in the irrigated valleys of northwest Mexico have increased dramatically from 1.0- to 1.3-Mg/ha range prior to 1950 to almost 5 Mg/ha in 1975 (Waddington et al., 1986). The yield improvement associated with release of semidwarf cultivars was discussed by Dalrymple (1986).

Grain yields of winter wheat in the Netherlands have increased from 3.8 Mg/ha in 1950 to 6.7 Mg/ha in 1982 (Spiertz & Vos, 1985). The yield improvements were attributed to modern cultivars that have greater resistance to lodging and greater efficiency in using larger amounts of fertilizer N, to higher harvest index, and to improved management. After about 1970, use of systemic fungicides, insecticides, and split applications of N further increased yields. Similar increased yields have occurred in other northwestern European countries (Vlassak & Verstraeten, 1985). Yields in excess of 10 Mg/ha have occurred in some production environments, but these high yields have not been repeatable in different climatic seasons. A record yield of 14.0 Mg/ha was reported in the state of Washington (Stanford & Legg, 1984).

The release of semidwarf cultivars with increased harvest index was primarily a one-time progress in incremental yield improvement, while release of newer cultivars has contributed to increased yields without further reduction in plant height (Dalrymple, 1986). Further releases of high-yielding cultivars of bread (Waddington et al., 1986) and durum (Waddington et al., 1987) wheats in northwest Mexico have shown genetic yield improvement associated with increased aboveground biomass, increased seed numbers per unit area (primarily by increasing seed per head), and increased total grain-filling rate. Yields of durum cultivars have been improved in association with shortening the time to anthesis and lengthening the grain-filling period. From this perspective, genetic yield improvement is being expressed through growth and development processes other than height reduction, and irrigation will continue to play an important role in realizing the higher genetic yield potentials in semiarid and arid environments.

In semiarid regions where seasonal precipitation is a significant contribution to water requirements, wheat is widely grown under limited irrigation with attainment of moderate yield levels. Under such conditions, yields obtained by farmers are normally much lower than those obtained from research station tests that are irrigated and managed for high yields. In India, state-irrigated wheat yields as a percentage of research station yields averaged 58% in Punjab and 30% in Madhya Pradesh and Utter Pradesh (Sinha et al., 1985). In the Murrumbridgee Irrigation Area (MIA) of southeastern New South Wales, Australia, irrigated wheat yields obtained by farmers averaged 2.6 Mg/ha, while yields on research plots managed for high yields averaged 6 to 8 Mg/ha (Smith et al., 1983; Steiner et al., 1985). Smith et al. (1983) compared irrigated wheat yields obtained in the MIA with those obtained in Yolo County, California, where irrigated wheat yields averaged 6.4 Mg/ha. Low irrigated yields in the MIA were attributed to high clay soils having low permeability, transient water logging following flood irrigation, and limited rooting depth (Smith et al., 1983).

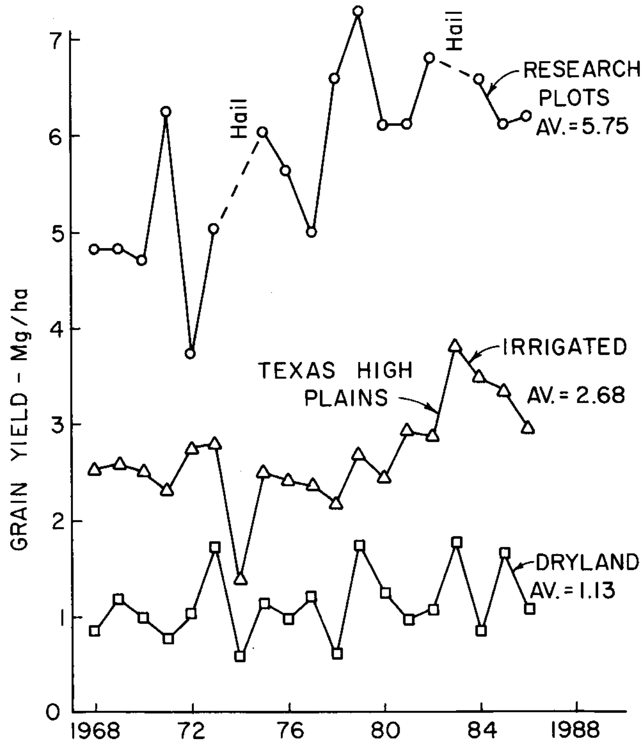

Fig. 20-2. Average farm irrigated and dryland yields, Texas High Plains, compared with the average yields of the five high-yielding varieties each year in irrigated wheat improvement research tests at Bushland, TX. Farm yields are from annual reports, Texas Agricultural Statistics Service.

Irrigated yields in the Texas High Plains are compared with dryland yields in Fig. 20-2. These irrigated yields in semiarid regions of limited groundwater supplies and significant seasonal rainfall average 47% of the average research plot yields by the five highest-yielding cultivars grown each year.

2. Yield Components

Yield component analysis involves viewing yield as the product of plants per unit area, heads per plant, spikelets per head, grain per spikelet, and weight per grain. The number of grain per head can be influenced by water deficits until a few days after anthesis, when the grain numbers are firmly set. Because of the plastic nature of the plant and associated negative correlations among the yield components, a simplified approach is combining the four grain number components into number per unit area. Thus, a yield component analysis can logically involve only two components: grain number per unit area and grain weight. The grain numbers component establishes the yield potential that is realized if conditions after anthesis are favorable for grain filling.

Grain-filling termination is influenced by availability of assimilates and/or nutrients (Gallagher & Biscoe, 1978). Water deficits after anthesis largely limit yields by reducing the photosynthetic rate and duration. As photosynthesis continues to decline during the latter phase of grain filling, relocation of preanthesis dry matter helps to sustain the grain-filling process. Grain weight often exceeds postanthesis dry matter increase, sometimes by as much as 50% under water deficits (Gallagher & Biscoe, 1978). The photosynthesis-assimilate relocation process influencing grain filling is less sensitive to water deficits than growth (leaf area and dry matter accumulation) and development processes that influence seed numbers per m^2.

The historic increases in wheat yields have involved improved cultivars that have increased spikelets per head, grain per spikelet, and higher grain weights and larger leaves (Evans & Dunstone, 1970). In an evolutionary perspective, higher grain weights have resulted from both faster and longer grain-filling periods (Sofield et al., 1977). While unit area photosynthesis rates of leaves have not increased in higher-yielding cultivars (Evans, 1981), modern production practices have resulted in high photosynthetic surface area (LAI of 4–8) that provides assimilate capacity to support both high grain numbers and high grain-filling rates associated with high yields.

3. Harvest Index

The above-ground components of the wheat plant were determined by weight as 40% grain, 33% culm, 10% chaff, 9% leaves, and 8% vegetative tillers (Singh & Stoskopf, 1971). Gifford and Evans (1981) indicated the best wheats now have *harvest indices* (HI, the grain fraction of aboveground dry matter by weight) around 0.50. A review of the literature indicates that the HI of modern high-yielding cultivars is mostly in the range of 0.38 to 0.50. The highest HI found in the literature was 0.60 for early-planted spring wheat cultivar 'Twin' in Utah (Hanks & Sorensen, 1984), while the lowest values of slightly <0.2 were found for winter wheat at Manhattan, KS (Asrar & Kanemasu, 1985), for wheat grown under major water deficits in southern Iran (Poostchi et al., 1972), and for wheat grown under severe stress after anthesis in Australia (Passioura, 1977).

Dry matter accumulation during head development proceding anthesis influences grain numbers (Fischer, 1985a); the more preanthesis dry matter produced, the more grain there is to be filled and the more critical the postanthesis water supply and dry matter accumulation becomes in preventing grain shrivelling and a low HI. Passioura (1977) found a linear relationship between HI and the percent of the seasonal water use after anthesis which ranged from HI of 0.2 when water use after anthesis was less than 5% of the season total to about 0.5 when water use after anthesis was 25 to 30% of the total. The results demonstrate grain filling as a critical stage for water deficit effects on HI.

Line source sprinkler irrigation studies involving water deficits normally are managed to distribute the deficits and, thus, distribute dry matter production throughout the season. Under this method of deficit management, Hanks and Sorensen (1984) found that HI was not affected until seasonal ET was reduced by over one-half. When ET was reduced to 33% (from 534–176 mm), HI for spring wheat varieties grown in Utah were reduced from 0.51 to 0.44.

Hanks and Sorensen (1984) determined that a range of five planting densities for spring wheat did not affect HI. However, high planting densities in winter wheat increases early season biomass and reduces HI. Darwinkel (1978) found that increasing planting density from 100 to 800 plants/m^2 decreased HI from 0.44 to 0.38. As higher planting densities increased heads per m^2 from 500 to 900, HI decreased from 0.47 to 0.43. When heads increased beyond 800/m^2, the decline in grain yields was associated with the lower HI.

A relatively wide range in planting dates for spring wheat in Utah, early April to mid-May, did not affect HI. However, a further delay in planting to late May reduced HI from 0.49 to 0.44 because of reduced grain yield (Hanks & Sorensen, 1984). Very early planting of winter wheat reduces HI by increasing early season biomass production.

Donald and Hamblin (1976), in a review of biological yield and HI, concluded that the application of N fertilizer to cereals commonly gives an increase in biological yield that is proportionately greater than the increase in grain yields and the HI declines. Data from 12 yr of tests at the Rothamsted Experiment Station indicated that increasing N application from 0 to 200 kg/ha decreased HI from 0.36 to 0.30. Data quoted from McNeal et al. (1971) indicated that increasing N application from 0 to 90 kg/ha for spring wheat in Montana decreased HI from 0.43 to 0.39.

Evans (1980) stated that the yield increase of wheat through 1976 came from the HI, which rose to about 0.50. Gifford et al. (1984) presented data for eight major winter wheat cultivars released in England over a period of 70 yr. Grain yield increased from 5 to 7 Mg/ha, while HI increased from 0.35 to 0.50, with the increased yields being associated with the increased HI.

Syme (1970) tested nine cultivars in which the HI ranged from 0.24 to 0.39 and found that increasing HI accounted for 92% of the yield variance. He indicated that the close correlation ($r = 0.96$) of HI with yield suggests improvement in this ratio may be associated with most of the varietal increase in wheat yield in Australia. A significant contribution to increased HI has been the development of semidwarf and dwarf cultivars. Singh and Stoskopf (1971) found that dwarf compared with tall cultivars increased HI from 0.38 to 0.42.

Austin et al. (1980) concluded that the newer, high-yielding cultivars were shorter and had lower culm weights per m^2 than older cultivars but similar maximum leaf areas and leaf weights per m^2. Total dry matter production was similar, and the increase in grain yield due to cultivar improvement was associated mainly with greater HI. They estimated the potential through breeding to increase HI from present values of about 0.50 to 0.60 and predicted further genetic gain in yield will depend on exploiting genetic variation in biomass production.

Other authors indicate that increased biomass, in addition to increased HI, has contributed to increased yields. MacKey (1973) presented wheat productivity data for 50 yr of winter wheat breeding in Sweden through 1955, in which grain yields were increased from 3.9 to 5.5 Mg/ha, and for 60 yr of spring wheat breeding (through 1965), in which grain yields were increased from 3.3 to 4.3 Mg/ha. The HI increased from 0.34 to 0.41 for both winter and spring types and was associated with about one-half the yield increase in winter wheat and about two-thirds of the yield increase in spring wheats.

More recent tests by Waddington et al. (1986, 1987) indicated that the increase in bread wheat yields for cultivars released since 1950 (5.5–7.8 Mg/h) and in durum wheat cultivars released since 1960 (3.7–8.4 Mg/ha) were associated with both increased HI and aboveground biomass. Harvest indices of bread wheats increased and peaked in 1968 with the release of 'Sonalika 68' (HI = 0.47), while HI of durum wheat cultivars peaked in 1975 with the release of 'Mexicali 75' (HI = 0.46). Continued increased yields from more recent releases have been entirely associated with increased biomass and seed numbers per head. The dramatic increase in irrigated durum wheat yields from 3.7 to 8.4 Mg/ha was associated with an increase in HI from 0.24 to 0.42 and an increase in aboveground biomass from 13.7 to 17.7 Mg/ha.

Dry matter (DM) at anthesis generates a sink that represents a given yield potential, as expressed through seed numbers per m^2. In modern short wheats, anthesis DM is approximately 1.5 times grain yield, while with tall cultivars, it is 2.0 or more. The favorable ratio by the short wheats may be further improved by nontillering uniculm types that offer prospects of increased yields. Atsmon and Jacobs (1977) determined HI of 0.41 for a tillered cultivar compared with 0.54 for a uniculm line that had 13% higher grain yield per plant. Darwinkel (1978) found that late-formed shoots at low plant densities reduced HI from 0.45 to 0.36.

In summary, the wheat plant conservatively adjusts grain numbers to preanthesis water deficit-induced reductions in dry matter to the extent that

HI is affected little, while HI is sensitive to postanthesis water deficits. Irrigation has played an important role in the understanding of HI relationships of wheat in some climatic environments by eliminating postanthesis water deficits.

4. Quality

Common wheats are classified for commercial purposes as being hard or soft, either red or white, and spring or winter. Durum wheat is considered separately in some areas but not in others (Shellenberger, 1978). Zeleny (1978) discussed the botanical, physical, and chemical criteria of wheat quality; more recently, Finney et al. (1987) discussed milling properties and bread-making properties of hard (bread) wheat, soft wheat, and milling and pasta-processing properties of durum wheats. The quality of wheat is usually determined by its suitability for a particular end use (Zeleny, 1978). Finney et al. (1987) described actual quality of a wheat as the summation effect of soil, climate, and seed stock on the wheat plant and kernel components.

The major environmental factors influencing quality (water, soil fertility, and temperature during grain filling) were discussed by Evans and Wardlaw (1976). Solar radiation has little effect on protein, since grain protein and starch accumulation are affected similarly by reduced radiation. Although soil water and fertility may influence many quality criteria, their effect on the quantity and quality of protein in wheat grain may be of the greatest significance.

Grain filling of wheats proceeds at a linear rate with time from about 15 to 85% of final grain weight (Gallagher & Biscoe, 1978). Under conditions of relatively high N where uptake continues through grain filling, both protein and starch content of the grain increase linearly until near physiological maturity. When soil nitrates are severely depleted by the time of anthesis and little uptake occurs during grain filling, most of the N accumulation in the grain is relocated from leaves and culms. Where low N is combined with adequate irrigation, leaf senescence is delayed, relocation of previously assimilated N to grain filling is slowed, and protein content of grain is reduced. Low protein contents, indicating N deficiency, are mostly in the range of 8.5 to 10.5%. Water deficits during grain filling accelerate leaf senescence, and relocation of N contributes to increasing protein at a time when wheat starch accumulation has slowed. Thus, low yields from water deficits during grain filling are generally accompanied by high grain protein contents. High protein contents are mostly in the range of 12 to 16%.

Finney et al. (1963) found that wheat samples harvested in 1962 from irrigated regional performance trials at a number of locations in the southern Great Plains had shorter mix times and lower corrected loaf volumes for protein content than samples from comparable dryland trials. Although these differences, in some cases, could be accounted for by differences in protein content of the samples, a generally longer fruiting period of irrigated wheat was believed to have contributed to the shorter mix times. Certain irrigated samples, particularly in 1972, appeared to have undergone protein degradation, as evidenced by mixing times and, in certain instances, by loaf volumes that were materially less than those of comparable dryland samples. Other irrigated wheats in 1958 and 1959 had fruiting periods that were not much longer than those for dryland samples and had mixing times that were equal to or longer than those of dryland wheats.

Loaf volume of bread wheats is linearly related to protein content of the flour. Where loaf volume was not limited by the effects of high field environmental temperatures, protein content accounted for 95% of the variability in volume (Finney & Fryer, 1958). Although high wheat protein content (up to 17–18%) normally contributes to increased gluten strength, Tipples et al. (1977) found that in several instances, irrigated hard red spring wheat with protein content of over 17% showed a marked weakening of physical dough characteristics and a deterioration of baking quality.

High temperatures (above 32 °C) during the latter part of the grain-filling period reduce protein content (Smika & Greb, 1973) and loaf volume (Finney & Fryer, 1958). Finney and Fryer (1958) found that varieties with long dough mixing times were more tolerant to detrimental effects of high temperatures on loaf volume. When considering temperature effects in subhumid eastern Kansas compared with semiarid regions of the Great Plains, Finney and Fryer (1958) indicated that the continuation of water use through grain filling reduces the detrimental effects of high temperatures on loaf volume. Musick et al. (1963) found that adequate irrigation increased loaf volume per unit of grain protein when compared with treatments that experienced water deficits. Canopy temperatures are normally cooler than air temperatures (Howell et al., 1986; Steiner et al., 1985) and improved protein quality may be associated with transpirational cooling. Evans et al. (1975) indicated that increasing temperature during grain filling has a similar effect to water stress on increasing grain protein. However, Smika and Greb (1973) found that the late grain-filling effect was curvilinear, with protein increasing as temperature increased from 22 to about 30 °C and then decreasing in the 32 to 37 °C range.

Irrigation, by reducing water deficits and increasing yields, strongly interacts with N fertility in influencing protein content and quality (Fernandez-G. & Laird, 1959; Musick et al., 1963; Jensen & Sletten, 1965; Bole & Dubetz, 1986; Eck, 1988). In studies in the southern High Plains, Jensen and Sletten (1965) found that lower rates of applied N increased yields with little effect on protein, while higher N rates had a reduced effect on yields per unit of N and an increased effect on protein content. Low N rates that increase relative yield in the range of 0.2 to 0.5 have been shown to reduce grain protein (Fernandez-G. & Laird, 1959; Strong, 1981).

The interrelationships of yield and protein content of wheat grown under adequate irrigation and involving water deficits during GS2 and GS3, along with N rates ranging from deficient to excessive for maximum yields, were reported by Musick et al. (1963) and Eck (1988). Where yields were reduced to about 0.5 by severe stress in the study by Eck (1988), applied N did not affect yields but markedly increased protein content within a range of 10.5 to 16%. As water deficits were reduced, applied N increased yields with only a modest increase in protein content until maximum yields were attained for the water level involved. After attainment of maximum yields, the increase in protein averaged 1% per 42 kg/ha of applied N to a maximum protein content of 16%.

The results by Eck (1988) were obtained on a slowly permeable clay loam that normally experiences low profile drainage and N leaching from irrigation. Ritter and Manger (1985) stated that NO_3 leaching, which can be substantial on some soils where all the N is applied before planting, is directly related to profile drainage volume and is associated with low irrigation application efficiencies. They recommended applying only enough N fertilizer to meet crop requirements for a realistic yield goal. However, some additional N application may be desirable to increase the protein content and improve baking quality of the irrigated hard red wheats. Spratt and Gasser (1970) found that N applied to spring wheat at boot stage increased dry matter much less than application at planting, but caused a greater increase in the concentration of N in the grain.

For quality of pastry flour, the soft white wheats should contain less than 10.5% protein (Bole & Dubetz, 1986). Adequate irrigation is required through grain filling to prevent excessive protein content. They indicated that excessive protein in soft wheats can be prevented by limiting fertilizer N plus soil NO_3 N to 30 kg/ha for each Mg/ha increase in target yield.

Finney et al. (1987) indicated that sufficient protein is necessary in durum wheat; generally, semolina protein of 11 to 12% (14% moisture basis) is sufficient for gluten strength. They also indicated that as with other classes of wheat, the protein content of durum is controlled by fertilizer, environment, and heredity and that the protein content of durum generally ranges over 13% in the whole grain.

Inherent differences in protein content occur among cultivars of all classes of wheat, but differences in protein of wheat of a given class are closely associated with cultural practices and environmental factors directly or as they influence yield. Johnson (1978) stated that protein levels of hard red winter wheat in the Great Plains began a steady downhill trend in 1964 as farmers became actively concerned with high-yielding wheat cultivars. In many cases, inherently high-yielding cultivars may sacrifice protein content for yield. However, this trend need not continue, for there are cultivars like the hard red winter wheat cultivar Lancota, numerous experimental lines, and germplasm releases that have the potential for elevated protein, even at high yield levels (Johnson, 1978). In addition, Stein et al.(1987) indicated that the use of the rapid near-infrared screening procedure for protein will permit simultaneous selection for both grain protein and yield.

Good quality, high-yielding irrigated wheat of all classes, as related to intended end use, is possible if proper attention is given to irrigation practices, soil fertility levels, other cultural practices, and cultivar selection.

II. EVAPOTRANSPIRATION

Evapotranspiration (ET) is a complex energy-driven process, but in simple terms, it is primarily influenced by the evaporative demand of the climate, the nature and extent of vegetative ground cover, the soil and plant water status, and the length of the growing season. Evapotranspiration and methods of measurements are discussed by Ritchie and Johnson (chapter 13 in this book) and by Hatfield (chapter 15 in this book). Evapotranspiration is widely used in determining water requirements, scheduling irrigations, and assessing crop growth and yield response to water and water deficits. In this section, we discuss a review of ET data by adequately irrigated wheat obtained from publications of field and lysimeter studies.

Papers from 26 studies containing seasonal ET data from sites in the USA, Britain, Zambia, Israel, India, and Australia were reviewed. The lowest seasonal ET values of 300 to 360 mm were measured from both short growing seasons in India (Prashar & Singh, 1963; Rao & Bhardwaj, 1981; Reedy & Bhardwaj, 1982) and a cool growing season at Copenhagen, Denmark (Mogensen et al., 1985). The highest seasonal ET of 818 mm was reported from Australia (Cooper, 1980).

Data from the different climatic environments indicated, in general, that for fall-planted spring wheat, the longer the growing season, the higher the seasonal ET. For the relatively short growing seasons, ET of 300 to 350 mm were measured in the India studies and in Zambia (Bunyolo et al., 1985). In the southwestern USA, where growing seasons are longer and development extends into periods of high temperatures, seasonal ET was measured in the 650 to 700 mm range in Arizona (Erie et al., 1973, 1982) and in the Imperial Valley, California (Ehlig & LeMert, 1976). Maximum daily ET rates are strongly influenced by climatic environment and average 2.5 to 3 mm/d in Britain (Monteith & Scott, 1982); 3 to 5 mm/d in the shorter seasons and, thus, in cooler environments of India and Israel where maturity occurred before high temperatures developed (Prashar & Singh, 1963; Shimshi et al., 1973); and 8 to 9 mm/d in the warmer environments during grain filling in the southwestern USA (Erie et al., 1982; Ehlig & LeMert, 1976). The maximum daily values for fall-planted spring wheat grown in the southwestern USA were similar to values for winter wheat grown in the central and southern High Plains (Jensen & Musick, 1960; Jensen & Sletten, 1965; Musick et al., 1963; Shawcroft & Croissant, 1986).

In the High Plains, seasonal ET has been measured in irrigation studies ranging in N latitude from 35 (Bushland, TX) to 38° (Garden City, KS) and 40° (Akron, CO). Seasonal ET at the three locations averaged 710 mm at Bushland (Jensen & Sletten, 1965; Schneider et al., 1969; Musick et al., 1984; Eck, 1988), 610 mm at Garden City (Musick et al., 1963), and 503 mm at Akron (Shawcroft, 1983). As latitude increased by 5° from Bushland to Akron, planting dates were advanced by about 3 wk, while anthesis dates were delayed by 3 wk. Thus, for winter wheats, lengthening the growing season by increasing latitude reduces seasonal ET in association with increased length of winter dormancy and lower temperatures during GS1 and GS2. Temperatures during GS3 in the irrigated production regions of the western High Plains are not appreciably different unless associated with differences in elevation; peak ET rates, as shown by studies at Bushland, Garden City, and Akron were similar (Jensen & Musick, 1960; Shawcroft & Croissant, 1986).

Daily ET rates for late fall-planted winter wheat were measured in lysimeter studies at Kimberly, ID, and compared with alfalfa as a reference crop (Wright, 1982). The ratio of wheat to alfalfa ET (basal crop coefficient) for a late fall planting increased to 1.0 after about 4 wk of spring growth. Normal planted winter wheat in Idaho that tillers extensively in the fall develops effective ground cover for a basal crop coefficient of 1.0 after about 2 wk of spring growth (Wright, 1982).

A ratio of daily measured lysimeter ET to Class A pan evaporation at Brawley, CA, indicated that fall-planted spring wheat reached the potential rate about 60 d after irrigation for emergence (Elhig & LeMert, 1976). Evapotranspiration continued at the potential rate of 0.8 of Class A pan evaporation for about 80 d before declining rapidly with loss of green vegetation.

Green LAI peaks before anthesis and gradually declines during grain filling, while ET increases due to increasing climatic evaporative demand, until it peaks at about milk stage. Seasonal ET curves suggest that the emergence of wheat heads and their prominence in interception of incoming solar radiation apparently does not result in reduced ET rates below potential. The ET decline below potential becomes pronounced during late grain filling as the loss of greenness accelerates approaching senescence. Wright (1982) indicated senesced wheat at maturity reaches a basal coefficient of 0.15 (a similar value to other senesced crops). Ehlig and LeMert (1976) indicated a low ET ratio to pan evaporation of 0.2 after surface drying following irrigation for emergence and a ratio of 0.15 after complete senescence. The lower value after maturity suggests the senesced canopy reduces soil evaporation.

III. WATER DEFICITS

A. Plant Water Deficits

Water relations of wheat were reviewed by Jones (1977) and Kirkham and Kanemasu (1982). According to Turner (1986), plants can be classified into thre categories for drought resistance. Wheat is classified in the category of "drought tolerance with low plant water potential." This drought resistance category has the following adaptation mechanisms: maintenance of turgor, osmotic adjustment, increase in cell elasticity, decrease in cell size, desiccation tolerance, and cell protoplasmic tolerance. Wheat is not sensitive to stomatal closure (Morgan, 1977), and Meyer and Green (1980) indicated that ET reduction under severe stress may result from increased soil-root resistance rather than stomatal control of water loss.

The drought tolerance of wheat reduces critical stage sensitivty for yield compared with many other crops and permits irrigation management involving a wide range of allowable water deficits. Wheat genotypes can range widely in osmotic adjustment (Morgan, 1977). However, in the southern High Plains, six commonly grown cultivars maintained leaf turgor pressures above 0.6 MPa under a wide range of water deficits, indicating marked osmotic adjustment (A.C. Mathers, 1985, personal communication). Minimum turgor pressures under severe stress were more than double those obtained from tests with corn, sorghum [*Sorghum bicolor* (L.) Moench], soybean [*Glycine max* (L.) Merr], and sunflower (*Helianthus annuus* L.). Osmotic adjustment may tend to be a characteristic of wheat varieties grown in semiarid environments since the varieties have been selected for performance under both irrigated and dryland conditions.

Winter wheat is grown in cooler environments than summer crops, and the normally slow development of water deficits in a field environment may contribute to the marked osmotic adjustment found in wheat compared with summer crops that experience more rapid stress development. When leaf water potentials of nonstressed wheat were in the range of -1.6 to -2.0 MPa, severely stressed wheat had potentials of -3.0 MPa by heading and to -4.0 MPa or lower during grain filling before leaf death occurred (Ehrler et al., 1978; Fischer & Sanchez, 1979; Sojka et al., 1981). Osmotic adjustment is influenced by solute accumulation in cells, and osmotic potentials vary in diurnal cycles similar to leaf water potentials (Morgan, 1984). When deficits are terminated by irrigation, cell metabolic processes may use the solutes and cause a loss of osmotic adjustment within a few days. Osmotic adjustment during stress contributes to maintaining turgor in developing heads prior to anthesis and in the developing root systems (Turner, 1986).

Papendick et al. (1971) found that winter wheat has the ability to deplete soil water on Ritzville loam (coarse-silty, mixed, mesic Calciorthidic Haploxerolls) to -4.0 MPa or lower and that the lower limit of soil water potential cannot be precisely defined. This remarkable ability of wheat to thoroughly deplete the profile of available water is likely associated with osmotic adjustment of roots, and Fischer (1980) suggested the maximum extent of root zone soil drying may be more dependent on plant water potential gradients than on rooting density.

Since plant water deficit values are sensitive to evaporative demand, their use in irrigation scheduling may require greater knowledge and sophistication than the use of soil water deficits. With experience, plant water deficit effects can be assessed visually in a qualitative way. Visual appearance of stress effects on reduced growth are extensively used in conjunction with development stages and the calendar for irrigation scheduling in the Great Plains.

B. Soil Water Deficits

The use of soil water deficits has a long history in irrigation scheduling and is receiving renewed emphasis in soil-water-plant relations studies. In reassessing plant adaptation to water deficits, Turner (1986) concluded that a reduction in leaf area appears to be largely affected by soil water status and root hydration and is a response rather than an adaptation to water deficits. Meyer and Green (1980), using lysimeters in South Africa, found that expansive growth declined when soil water in a 1.0-m profile was depleted below 33% available. To prevent the reduction in expansive growth, which was also influenced by temperature and evaporative demand, they recommended irrigation scheduling based on 50% available soil water (ASW) depletion. The decline in ET did not occur until depletion was below 20% ASW.

Musick et al. (1976) found that in the southern High Plains, soil water depletion to the −1.5-MPa potential, 1.2-m profile depth, resulted in a 20% yield reduction in relatively dry seasons and no reduction in a season when profile drying occurred in conjunction with periodic rewetting of the surface soil by rainfall. These studies, conducted on Pullman clay loam (fine, mixed, thermic family of Torrertic Paleustolls), indicated the ability of wheat under prolonged stress to deplete profile water to about 50 mm or 35% below the −0.03- to −1.5-MPa field capacity to wilting point water content range. When Jensen and Sletten (1965) weighted the water potentials of the root zone by 4, 3, 2, and 1 to correspond to an approximate 40, 30, 20, and 10% depletion pattern by rooting depth increments for irrigated crops, ASW depletion to −0.4 MPa did not affect yields, but depletion to −0.9-MPa potential reduced yields by 17%.

Plant water deficits can be taken as predawn water potentials that approach root zone soil water potentials. Sojka et al. (1981) found that a decline in predawn potential to −0.7 MPa on a clay soil in northwest Mexico resulted in 40% yield reduction. When severe deficits were terminated by irrigation, wheat rapidly recovered to normal water potentials of nonstressed wheat.

Simulation modeling can be useful in assessing optimal irrigation policy. An optimized simulation study by Yaron et al. (1973) indicated depletion of ASW to 13% for a loess (silt) profile to 1.5-m depth. The results were similar to results obtained from field tests on a deep loess profile by Musick et al. (1963) in southwest Kansas. Depletion of ASW (1.8-m depth) to 10% during milk stage reduced yields by 6% and increased water-use efficiency (WUE).

The recommendation by Meyer and Green (1980) that irrigation be scheduled by 50% ASW depletion to prevent reduction in expansive growth may not apply to water-yield optimization of winter wheat when some reduction in expansive growth is allowable. Before the introduction of the stiff straw semidwarf cultivars in the Great Plains, reduction in expansive growth during early GS2 by delaying irrigation was commonly practiced to limit height and lodging. Spring wheat is more susceptible than winter wheat to early GS2 soil water deficits because of a less developed root system (Gales, 1983). Growth of the root system increases the allowable soil water depletion before deficits become limiting to growth.

IV. IRRIGATION MANAGEMENT

A. Irrigation Water Requirements

Irrigation water requirements consist of initial application for crop establishment and recharging the soil profile, and seasonal irrigations to meet ET demands. Seasonal irrigation requirements can be predicted based on water budget procedures using available soil water storage, allowable depletion level, ET prediction, and irrigation application efficiency (see chapter 17 in this book). Irrigation water requirements include losses associated with application efficiencies. In the Texas High Plains, furrow application efficiencies were estimated from irrigation inventories as mostly in the range of 50 to 80% without considering tailwater reuse and were higher on the slowly permeable clays. Sprinkler application efficiencies were measured from 223 field evaluations of center pivot systems as mostly in the 80 to 90% range and were higher under lower windspeeds (Musick et al., 1988).

Several studies have related ET and irrigation requirements for wheat to the National Weather Service Class A pan evaporation (E_{pan}) (Miller & Hang, 1982; Agarwal & Yadav, 1978; Bunyolo et al., 1985; Choudhary & Kumar, 1980; Jalota et al., 1980; Prihar et al., 1976; Singh, 1978). Evapotranspiration averaged approximately 0.8 of E_{pan} after full ground cover (Ehlig & LeMert, 1976; Shimshi et al., 1981).

Wheat normally develops full ground cover before seasonal irrigations are needed. Irrigation studies in India indicate that application based on 0.75 to 0.8 of E_{pan} provided adequate water, while Miller and Hang (1982) found that daily sprinkler application based on 0.95 E_{pan} replacement on a relatively high water-storage soil was excessive and caused yield reduction. A daily deficit application of about 0.4 E_{pan} resulted in maximum yield of winter wheat in a moderate evaporative demand climate at Prosser, WA, when the irrigation season was started with a wet soil profile. The study by Miller and Hang (1982) demonstrates the success of allowing depletion of profile soil water while avoiding critical water deficits. Critical deficits were minimized by the daily deficit irrigations that allowed plant conditioning to slowly developing water deficits.

In India, where the common practice is to apply five seasonal irrigations based on stage of development, a scheduling procedure based on water application as 0.75 E_{pan} permitted deleting early season irrigations and reducing irrigation water requirements (Prihar et al., 1976). This study demonstrated the value of an irrigation scheduling method that adjusts water application to climatic evaporative demand and allowable soil water depletion, particularly for wheat grown on high water-storage soils.

1. Preseason Irrigation

Irrigation management has emphasized beginning the growing season with a wet soil profile. In regions where rainfall is inadequate for soil profile wetting, emphasis has been given to an irrigation before planting or for crop emergence when planted into dry soil. In areas with dry seasons, an irrigation may be applied before planting to facilitate tillage and seedbed preparation and to control crop volunteer plants and weeds (Echert et al., 1978). In the study by Echert et al. (1978), seeding into dry soil and irrigation for emergence successfully replaced the preplant and the first postplant irrigation and the reduced application greatly reduced drainage losses to groundwater. In areas of dry summers and late fall and winter rainfall, seeding into dry soil and irrigating for emergence results in planting on an optimum date for growth and yield and is an efficient water management practice.

In the Great Plains, irrigated wheat is mostly planted as continuous cropping, after summer fallow, or, to a lesser extent, after harvest of a summer crop such as corn. The priority for water supplies from wells is usually given to summer row crops, and preplant irrigation is not commonly practiced because of conflicts in water demands. Germination results from seeding into moist soil, from rainfall after planting, or from an emergence irrigation. A common practice is to apply the initial irrigation sometime after emergence to rewet the soil profile. When soil water conditions are adequate for a period of growth after emergence, the initial irrigation may be delayed or deleted. The use of summer fallow for soil profile water storage at planting reduces the need for an initial irrigation before a period of substanital water use by the crop.

Because of primary tillage effects on increasing water intake, application amount by surface methods during an initial preplant or emergence irrigation frequently is about double that normally applied in subsequent seasonal irrigations (Jensen & Sletten, 1965). Due to surface sealing and runoff problems, large sprinkler applications are not made on bare soil, and preplant or emergence irrigation to recharge the soil profile is not normally practiced.

2. Seasonal Irrigation

Irrigation of wheat is widely practiced in regions where seasonal irrigation by surface methods ranges from only one application to as many as six or seven, depending on seasonal ET requirements, initial soil water storage, seasonal rainfall, application amounts, and yield goals. Where irrigation is practiced as a supplement to rainfall, such as in Israel, the common practice is to initially irrigate after seeding into dry soil for timely stand establishment and to apply a second irrigation for grain filling, depending on April rainfall (Shimshi et al., 1973). When wheat is grown as a dry season crop, an adequate irrigation level that does not limit ET and yields can be four to five applications in India (Lal, 1985); three to four applications in Arizona (Erie et al., 1973); five to seven applications in the Imperial Valley, California (Ehlig & LeMert, 1976); six to seven applications in northwest Mexico (Fischer et al., 1977); and seven applications in southeast Australia (Cooper, 1980). In many of these studies where frequent irrigations were applied, high yields attained were in the 7 to 8 Mg/ha range. On slowly permeable clays, the practice of frequent irrigation may not appreciably increase irrigation water requirements because low permeability limits water intake and application amounts during irrigation.

In the semiarid Great Plains, precipitation frequencies decline in the fall as the crop is established, increase with spring growth, and peak during grain filling. Irrigated wheat production is mostly concentrated on the fine-textured soils that are moderately deep and relatively high in water storage. Tests at Garden City, KS (Musick et al., 1963; Hooker et al., 1983), and at Akron, CO (Shawcroft & Croissant, 1986), indicate that when an initial irrigation is used to wet the profile, seasonal irrigation is not needed before boot stage, and irrigation that rewets the profile at this stage provides the irrigation water requirements for high yields. Precipitation during grain filling reduces and frequently eliminates the need for a second spring irrigation. In the central Great Plains, where sprinkler irrigation is practiced on relatively high water-storage soils, restricting water application to the boot to heading period reduces the risk of lodging (R.W. Shawcroft, personal communication).

In the Texas High Plains, wheat is mostly grown on slowly permeable clay loams that are surface irrigated. Three to four seasonal irrigations are required to meet ET demand and produce high yields (Jensen & Sletten, 1965; Schneider et al., 1969; Musick et al., 1984). When fine-textured soils such as Pullman clay loam are fully wet in the fall, a common irrigation schedule is to apply the first irrigation by jointing stage, the second during boot stage, and the third during grain filling. In a 5-yr test, Musick et al. (1984) found that during 2 yr when spring rainfall was above normal, no yield response occurred from an irrigation during grain filling. When wheat was irrigated in the fall on Sherm clay loam (fine, mixed, mesic family of Torrertic Paleustolls) at Etter in the Texas High Plains, yield response occurred from irrigation during jointing in April but not from irrigation during tillering in March (Shipley & Regier, 1972b). In south-central Washington on Ritzville fine sandy loam (coarse-silty, mixed, mesic family of Calciorthidic Haploxeralfs), Robins and Domingo (1962) found that when wheat was initially irrigated to begin the season with a wet profile, further irrigation was not needed until boot stage. Delaying irrigation past early vegetative growth reduced height and lodging with little or no reduction in grain yield. In the climatic environment of dry summers in the Pacific Northwest, irrigation of spring wheat during grain filling was necessary for high yields (Robins & Domingo, 1962).

B. Critical Stages

With wheat, a crop that has excellent drought resistance, development stages are not as critical as for other crops that are more sensitive to critical-stage water deficits. However, the critical stage terminology is extensively used in the literature for irrigation of wheat to indicate that some stages are more critical than others. Sensitivity to water deficits most frequently relates to physiological and morphological responses that reduce seed numbers per m^2. However, studies have reported critical stage effects that range from crown root initiation (tillering) to grain filling.

As a cool-season crop, wheat is mostly grown in relatively low to moderate evaporative demand climates. Under these conditions, stress normally develops slowly in a field environment, and adaptive response can limit yield reductions. Since critical stage effects are normally more pronounced through their effect on the grain yield component of grain number per m^2, they are more likely to occur during preanthesis. However, both the evaporative demand and the rapidity of water deficits increase as the season progresses; some studies have reported the critical stage effect as continuing well into grain filling (Misra et al., 1969; Schneider et al., 1969; Shipley & Regier, 1972b).

In controlled environment studies, Fischer (1970) reported the most critical stage as 10 d before anthesis. In later field studies of wheat grown in dry seasons in northwest Mexico, Fischer et al. (1977) reported the most sensitive stage as 25 d before to 20 d after head emergence (to about one-half grain filling). Milk stage, which occurs at about one-half grain filling, is the most sensitive stage for hot, dry wind effects of shrivelled grain and is prob-

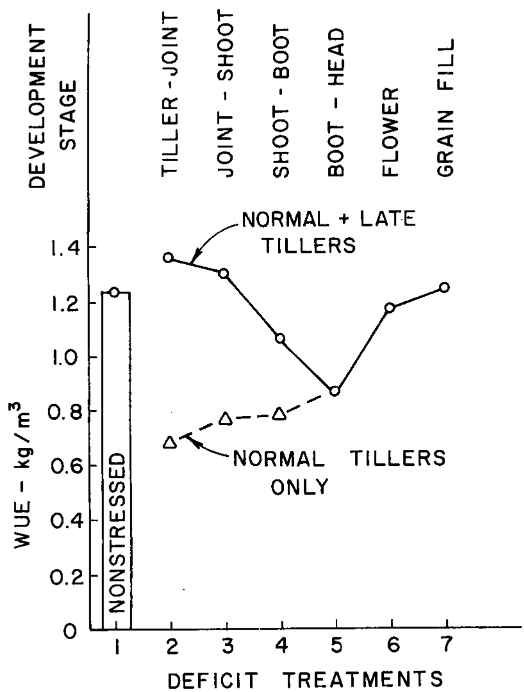

Fig. 20-3. Development stage effects of water deficit periods from tillering to grain filling of spring wheat on water-use efficiency (WUE), including stress-recovery compensation by late-developing tillers through boot stage (Copenhagen, Denmark, 55 °N) (adapted from Mogensen et al., 1985).

ably a combined effect of high temperature and lowered plant water potential (Fischer, 1980). Sensitivity to hot, dry winds on grain shrivelling is reduced by high soluble sugars (5–7%) in plant culms at anthesis. Late grain filling is less sensitive to water deficits, primarily because of relocation of preanthesis assimilates to grain filling. Major depletion of profile soil water storage after milk stage is commonly practiced and contributes to efficient water use. Also, in the Great Plains, increasing spring rainfall often limits the extent of water deficits during grain filling.

Studies that report crown root initiation (CRI) as the most critical stage involve fall seeding of spring wheat on sandy soils in the Indian subcontinent (Agarwal & Yadav, 1978; Choudhary & Kumar, 1980; Gajri & Prihar, 1983; Lal, 1985; Singh et al., 1979a). In studies on a clay soil, Fischer et al. (1977) found that crown roots become established from irrigation at planting and that delay in irrigation past CRI from 27 to 50 d did not affect yield, while Srivastava and Bansal (1975) found that a 2-wk delay on mixed black soils did not affect yield. Although the CRI irrigation enhanced rooting in sandy soils (Singh et al., 1979a), the yield response is more likely associated with increased tillering (Gajri & Prihar, 1983) and head numbers per m^2 (Agarwal & Yadav, 1978). In this short growing season environment, the adjustment in increased seed per head failed to compensate for the water stress effects on reduced tillering. In studies at Copenhagen, Denmark (55 °N lat), where spring wheat is grown as a summer crop, the tillering to jointing stage was determined by Mogensen et al. (1985) as the most critical if late developing stress-recovery tillers were excluded. Development stage effects of water deficit periods from tillering through grain filling on WUE are illustrated in Fig. 20–3. The compensation effect of late stress-recovery tillers declined to zero by boot stage, and boot to heading was determined as the most critical stage on yields and WUE.

In the southwestern USA, an initial irrigation (preplant or emergence) provides soil water storage that limits the development of critical water deficits during tillering; the jointing stage becomes critical (Day & Intalap, 1970; Ehlig & LeMert, 1976). In the study by Day and Intalap (1970), a stress period during jointing reduced seed numbers per m^2 by 45%. Stress during flowering and grain filling were only modestly less critical than during jointing, indicating only moderate differences in development stages to stress sensitivity.

Winter wheat grown in the Great Plains has a relatively long period for tillers to develop prior to FI, and tillers and potential head numbers are not usually critical yield components. The critical stage is reduced grain numbers per m^2, both as a combined influence of fewer heads (tiller senescence) and fewer seeds per head. This stage has been indicated as critical for irrigation by Musick et al. (1963), Shipley and Regier (1972b), Robins and Domingo (1962), and Schneider et al. (1969). In areas having a Mediterranean climate, irrigation may be needed only for timely establishment of the crop near the end of the dry season and to insure grain filling after the rains stop (Shimshi & Kafkafi, 1987); thus, grain filling becomes a critical stage for irrigation.

C. Water-Yield Relationships

Water-yield relationships have been determined between ET and yield and between irrigation water and yields. Relationships between ET and yield have been determined as both linear (Hunsaker & Bucks, 1987; Steiner et al., 1985) and curvilinear (Ehlig & LeMert, 1976; Musick et al., 1963; regression analyses of data by Sharratt et al., 1980). In addition, linear relationships have been determined from ET deficits during selected growth stages by Schneider et al. (1969) and during postanthesis grain filling by Aggarwal et al. (1986). In the high seasonal ET range, a decline in the yield response can be influenced by ET data calculated from soil water depletion that included some profile drainage (Sharratt et al., 1980).

In the high yield range, dry matter may be more responsive to increased ET than grain yield. Shipley and Regier (1972b) found that irrigation during early GS2 increased straw yields by 24% but had no effect on grain yields, since grain numbers per m^2 were not increased. When water deficits were limited to late GS2 and GS3 at Akron, CO, the ET-yield relationship was linear. However, irrigation applied during early GS2 increased ET but reduced grain yield, causing the ET-yield relationship to become curvilinear (Shawcroft, 1983). In the studies where the ET-grain yield relationship is curvilinear, the response decreases with increasing ET (Ehlig & LeMert, 1976; Musick et al., 1963).

Yield relationships to applied irrigation that exclude surface runoff are curvilinear diminishing return functions when the range in water applied is due to differences in scheduling (Echert et al., 1978; Hunsaker & Bucks, 1987;

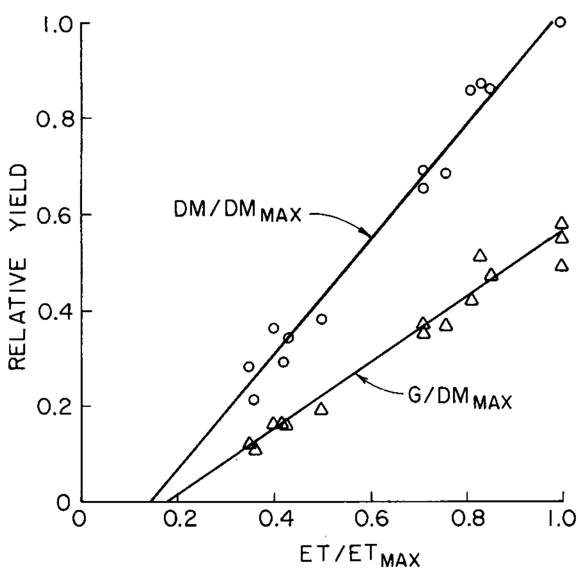

Fig. 20-4. Relative yield relationships of spring wheat dry matter (DM) to nonstressed DM_{max} and grain yield to DM_{max} over a range of water deficits (relative ET/ET_{max} of 0.35–1.0) from a sprinkler line gradient test that varied application depths only (adapted from Sharratt et al., 1980).

Shimshi, 1979). The exception may be water applied by the sprinkler line gradient method, which can be managed to vary only the amount applied without varying the timing (Sharratt et al., 1980). When profile drainage is avoided and profile storage is mostly depleted by maturity, water applied is utilized as ET and the water applied-yield relationships can become linear. An example of linear relationships of dry matter and grain yield, with ET expressed on a relative basis of ET_{max} and dry matter and grain yield expressed on a relative basis of DM_{max}, is illustrated in Fig. 20-4. The relationships in Fig. 20-4, calculated from sprinkler line gradient data by Sharratt et al. (1980), illustrate the grain yield threshold (about 0.2 ET_{max}) before the first yield increment and the stable HI when the grain yield is visually shown as a fraction of the dry matter.

D. Water-Use Efficiency

Water-use efficiency is defined as grain yield per unit of ET and is expressed as kg/m^3. Water-use efficiency of fall-planted irrigated spring wheat frequently is in the range of 1.0 to 1.2 kg/m^3 (Aggarwal et al., 1986; Bunyolo et al., 1985; Cooper, 1980; Lal, 1985; Shimshi & Kafkafi, 1978; Singh & Dastane, 1971). Some irrigation studies have resulted in a higher range of WUE, such as 1.5 to 1.9 kg/m^3 by Rao and Bhardwaj (1981), 1.4 to 1.5 kg/m^3 by Ehlig and LeMert (1976), and 1.2 to 1.6 kg/m^3 by Fischer (1970). Several studies have indicated that WUE values are higher under deficit conditions, especially when irrigation is applied in relation to critical stages (Ehlig & LeMert, 1976; Fischer, 1970; Lal, 1985; Miller, 1977; Rao & Bhardwaj, 1981; Schneider et al., 1969; Singh et al., 1979b). Effects of development stage deficits on WUE that indicate a critical stage effect during boot to heading are illustrated in Fig. 20-3.

Although irrigated wheat can be grown over a relatively wide range of water deficits and yields, the use of irrigation to manage water deficits normally prevents the reduction of WUE. However, in dryland cropping where water deficits cannot be controlled by irrigation, the severe deficits that occur in the southern High Plains can considerably lower WUE. In 25 yr of dryland wheat after summer fallow at Bushland, TX, WUE averaged 0.35 kg/m^3, for average yields of 1.1 Mg/ha (O.R. Jones, 1987, personal communication). Water-use efficiency of dryland wheat averaged about one-half the WUE of irrigated wheat grown over a wide range of water deficits with yields of 3 to 6 Mg/ha (Musick et al., 1984).

Water-use efficiency values are sensitive to yield levels and have substantially improved with the release of higher-yielding cultivars. In the southern High Plains, WUE increased from 0.44 kg/m^3 with 'Concho' grown in the late 1950s (Jensen & Sletten, 1965) to 0.54 kg/m^3 with 'Tascosa' grown in the late 1960s (Schneider et al., 1969) to 0.94 kg/m^3 with semidwarf cultivars grown during 1979 to 1982 (Musick et al., 1984). Irrigation tests in the Great Plains, Washington, and Utah have indicated WUE values to be mostly in the 0.8 to 1.0 kg/m^3 range (Miller, 1977; Musick et al., 1984; Sharratt et al., 1980; Shawcroft, 1983). Where the ET-grain yield relationship is linear, the response slope reflects a higher WUE value than for the maximum ET-yield value. For example, Steiner et al. (1985) determined by linear regression a response slope value of 1.6 kg/m^3 compared with WUE of 1.3 kg/m^3 for maximum yield.

The WUE of seasonal irrigations (IWUE) applied to level plots without surface runoff is usually similar to or only slightly lower than seasonal WUE values (Musick et al., 1984). However, IWUE values can be quite low when irrigations are applied that result in low yield response, and low IWUE values are more likely to occur in the higher water application and yield range.

V. PLANT NUTRITION

A. Fertilizer Requirements and Nutrient Uptake

Fertilizer requirements and nutrient uptake are the supply and demand sides of an equation that is influenced by many other factors. For N, the supply side includes soil-available N at planting and a somewhat uncertain quantity of N mineralized during the growing season. Also, some irrigation waters provide a significant source of N. Factors such as soil water, climatic conditions, cultural practices, and plant growth and development affect the uptake of N; the total plant need for N is somewhat difficult to accurately predict.

Irrigated wheat is mostly grown in semiarid to arid regions where soils are not deficient in K; thus, studies have emphasized N and P deficiencies and fertilizer requirements. Nitrogen is the plant nutrient that is normally most limiting and has been given the most emphasis in research.

Uptake efficiencies of applied N can be influenced by many variables and range from about 40 to 80%. When the N supply is variable over a wide range from severely depleted to luxurious, plant N concentration relative to dry weight is also variable (Viets, 1965). In a water-fertilizer study involving applied N rates of 0, 70, 140, and 210 kg/ha, Eck (1988) found near maximum grain yields of 6 Mg/ha with 140 kg/ha of applied N, which resulted in above-ground N uptake of 150 kg/ha. The 210 kg/ha rate failed to further increase grain yield but increased N uptake to 174 kg/ha.

Estimates of nutrient uptake for wheat yields of 6.7 Mg/ha by the Soil Improvement Committee, Fertilizer Association (1975) were 196, 39, and 130 kg/ha for N, P, and K, respectively. Several publications reporting results of irrigation-fertility studies indicate N fertilizer requirements for maximum yields with adequate irrigation to be in the range of 80 to 140 kg/ha, while maximum applied rates were as high as 220 kg/ha.

Phosphorus fertilizer requirements for maximum yields were mostly in the 20 to 40 kg/ha of applied P. Phosphorus fertilizer uptake is most efficient when band-applied near the seed at planting. A large broadcast application can be adequate for multiple crops, but total uptake efficiencies may be reduced. Land leveling is common in surface irrigation. Since P levels are frequently higher in the surface soil, removal of surface soil can result in P deficiency.

The ability of soils to supply N requirements of irrigated wheat varies widely, ranging from no more than 5% in some desert soils that are low in organic carbon to some productive soils high in organic carbon that can supply adequate N. In the water-fertility study by Eck (1988) on Pullman clay loam (1.5% organic carbon in 0.3-m depth), growing season mineralization of N supplied 60 kg/ha for irrigated wheat.

Wheat requires approximately 30 kg/ha of available soil N per Mg of grain produced (Tucker & Murdock, 1984). In the southern Great Plains, where irrigated wheat is grazed during the fall and winter and then managed for grain production, additional applied N of about 20 kg/ha is needed per additional Mg/ha of forage production available for grazing (Tucker & Murdock, 1984).

Under irrigation, applied N rates for the southern Plains and intermountain states range as high as 180 kg/ha (Tucker & Murdock, 1984; Westfall, 1984). On the slowly permeable clays with low leaching losses, N is mostly applied before planting as anhydrous NH_3. Split applications are more common on the moderately permeable soils that experience deep percolation of water and leaching of N. On these soils, a common practice is to apply one-half before planting and the remaining one-half during early spring tillering before rapid growth begins. Wheel track damage from ground-driven application equipment is less during tillering than later during culm elongation (jointing). When tractor passes after jointing are required for multiple applications of N or other chemicals, unplanted rows as traffic zones can minimize damage to the growing crop.

Under sprinkler irrigation, N solutions can be injected into irrigation water and applied in single or multiple applications. Injection of N into furrow irrigation water is not commonly practiced because of nonuniform application and losses in tailwater runoff. Soil tests are recommended for determining residual nitrates before planting and for estimating fertilizer requirements. Plant analysis can be useful in assessing N deficiency. Both total plant N uptake (aboveground) and NO_3 concentration in cell sap may be used. However, reliable, rapid methods of measuring tissue N status are lacking. Nitrogen may be applied late in the season to increase grain protein content and to correct late-season N deficiency associated with excessive irrigation and N leaching.

High levels of crop residues at planting in conservation tillage systems increase the need for applied N. Saffigna et al. (1982) found that 5 kg/ha of applied N was immobilized per t of incorporated residues. Frequent irrigation that maintains moist soil may increase N uptake compared with less frequent irrigation that allows the surface soil layer to remain dry for extended periods of time (Strong, 1981).

B. Growth and Yield Responses

Plants growing on soils that are deficient in N respond to fall N application by increasing seminal rooting (Richman et al., 1985). Since the seminal root system develops early, fall-applied N increased rooting to a much greater extent than spring-applied N. Applied N increases tiller development and associated nodal root development (Black, 1970a; Woodruff, 1980) and reduces tiller abortion during jointing (Power & Allesi, 1978; Rickman et al., 1985).

Nutrient deficiencies cause interruption of the tillering process by preventing elongation of auxilliary buds and by reducing the growth rate of the youngest tillers (Malse, 1985). The slowing of growth spreads progressively to older tillers, then to the main culm. For younger tillers, reduction in growth rate can be rapid and lead to senescence.

Black (1970a) found that early formation of nodal roots was necessary for tillers to develop and produce heads and that the increased heads per m^2 accounted for 97% of the yield response to applied P. Woodruff (1980) found that banded P increased nodal roots and tillers and P uptake to a greater extent than broadcast P. Nodal root development is necessary for adequate N and P uptake by tillers. Deficiencies of N and P can cause cessation of growth (Malse, 1985). Dryness of the surface soil reduces nodal root elongation and N uptake by tillers, thus increasing tiller senescence. Tiller senescence can be identified by yellowing of the terminal leaf.

Except in extreme conditions, nutrient deficiencies do not affect morphological development. Grain yields are reduced through reductions in growth rate and dry matter accumulation and are expressed through the reduction in grain numbers per unit area (both reduced head numbers and grain per head).

Nitrogen deficiencies cause protein deficiencies in leaves, which reduce photosynthesis, leaf area expansion, and dry matter accumulation and ac-

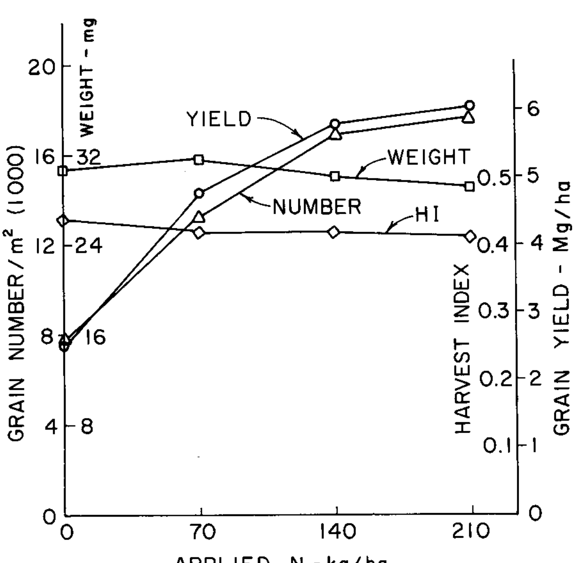

Fig. 20-5. Effect of N application on grain yield and harvest index (HI) and on the yield components of grain numbers/m^2 and weight for adequately irrigated winter wheat, Bushland, TX (adapted from Eck, 1988).

celerate senescence. It has been shown that N application increases the N content of leaves and delays senescence, which, in the absence of water deficits and high temperatures, extends the grain-filling period (Spiertz & Ellen, 1978). After anthesis, N compounds are relocated from vegetative parts and roots to filling grain (Gregory et al., 1981). Under adequate irrigation and fertility, N available for relocation can be estimated from the difference between the N content at anthesis (about 150 kg/ha) and the N residue in straw and chaff (about 60 kg/ha).

Late-season lodging is a problem associated with excess N and adequate irrigation. Excess N increases luxuriant growth and susceptibility to lodging, while lodging reduces photosynthesis and grain-filling rates and cause shrivelling of grain. The irrigated semidwarf cultivars with stiff straw have greatly reduced lodging problems associated with excess N. This has permitted the use of higher water and fertility levels for increased yields.

Increased yields from applied N are entirely associated with the grain yield component of grain numbers per unit area. In some studies, a fertilizer response that increased grain numbers per m^2 was associated with a slight to modest decrease in grain weight (Shimshi & Kafkafi, 1978; Eck, 1988). Also, the partitioning of dry matter into grain is affected little by N fertilization.

The yield components' responses to applied N are illustrated from data by Eck (1988) (Fig. 20-5). Yield response to applied N under adequate irrigation was about equally accounted for by increased head density and increased grain numbers per head. However, the yield component response to applied N may be cultivar-specific. The high early-season uptake of N and the sensitivity of tiller and floral development to N deficiency suggests

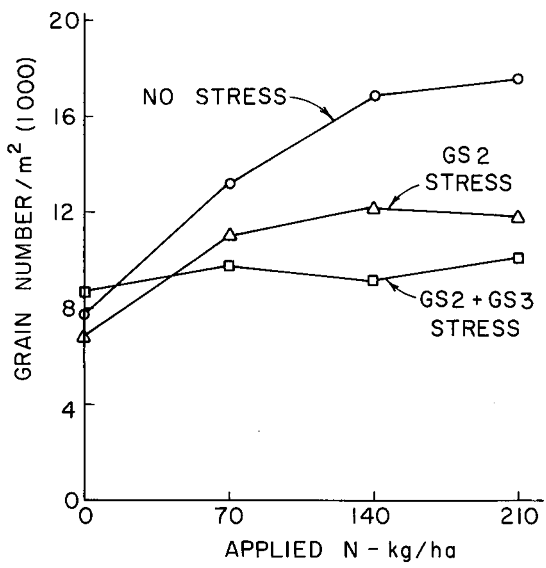

Fig. 20-6. Interactions of water deficits and applied N on grain numbers/m^2 for winter wheat at Bushland, TX (adapted from Eck, 1988). Yields were highly correlated with grain numbers/m^2.

that N application should not be delayed past early GS2. If deficiencies develop during rapid growth, further application may be needed and, under sprinkler irrigation, can be readily applied with the water. Late season-applied N can be effective in increasing grain protein content.

The interaction effects of water and N deficits are primarily expressed through the yield component of grain numbers per m^2. Water and applied N treatments from the study by Eck (1988) illustrate the interaction (Fig. 20-6). A reduction in yields by about one-half due to severe water deficits (during GS2 + GS3) or by a severe N deficiency where none was applied, both had a similar effect in reducing grain numbers per m^2. As the deficits in both water and applied N were conjunctively reduced, grain numbers per m^2 and yields were proportionately increased. Water deficit effects on growth and development normally occur during mid to late season, while major N deficiencies normally develop early and persist. Since water deficits are likely to increase in severity late in the season, they affect both grain numbers and grain weight, while early developing N deficiencies appear to only affect the grain numbers per m^2.

Economic models that use production functions and marginal analysis (additional yield from one additional input unit) are useful in optimization of water and fertilizer inputs. Applied water and N response are normally expressed as curvilinear diminishing return functions. Kloster and Whittlesey (1971) concluded that since the marginal yield response to water and N declined with increasing input, management for maximum yields is inconsistent with profit maximization and economic efficiency in allocating resources. Resource optimization and maximizing net returns are discussed in chapter 17 of this book.

VI. CULTURAL PRACTICES

A. Planting Dates

In most climatic regions in the Northern Hemisphere, winter wheat is planted from about mid September to mid- or late October. In the central and southern Great Plains, where irrigated winter wheat is planted for both grazing and grain production, planting dates are advanced to late August. Very early planting without grazing can cause excessive vegetative growth and increases seasonal water use and the risks of abortive loss of the advanced culms. Loss of culms can result from over-winter lodging of lush growth. In addition, early-planted winter wheat is more likely to be affected by diseases such as leaf rust, viruses, and root and crown rots.

Early planting advances spring development, which increases the vulnerability to freeze damage with culm elongation and elevation of the head above the soil surface. George (1982) indicates −5 °C as a critical temperature for 50% culm sterility when developing heads were 50 to 100 mm above the soil surface.

Late-planted winter wheat can encounter cold temperatures that limit tillers, roots, and leaf area growth which can be associated with reduced yields (Thill et al., 1978). The delay in tillering until temperatures warm in late winter and early spring limits the extent of tillering prior to cessation with FI (Porter, 1985), and delayed planting may necessitate the use of higher seeding rates for adequate head density and yield potential. At higher elevations in the lower latitudes, spring types should be planted late enough in the fall to avoid freeze damage prior to and during the sensitive flowering period.

At lower elevations in the lower latitudes, early planting is desired for development of GS2 and GS3 during the cooler months (Midmore et al., 1984). In these environments, growth continues during the winter and later planting can shift GS2 and GS3 to periods of increasing temperatures that reduce grain numbers per m^2 and grain-filling duration. In higher latitude environments, spring wheat is normally planted as soon after winter as conditions permit (early April through early to mid-May). Delayed planting past mid-May and associated delayed maturity can increase the risk of adverse weather conditions during harvest. In the southern part of the Great Plains winter wheat region, where fall-planted spring wheat may not survive the winter, spring wheat can be planted in February or March, but yields are usually lower than for fall-planted winter wheat.

Fischer (1981b) presented data from studies of fall-planted wheat in five regions that indicated yield reductions per week of delayed planting past the optimum as latitude at location sites declined from 40 °N lat to 18 °S lat. For two locations in India, the yield reductions were 10% per wk at 18 °N lat and 7% at 28 °N lat. For two locations in Australia, the reductions were 6% per wk at 31 °S lat and 4% at 35 °S lat; and for one location in Turkey, 5% at 40 °N lat. About a 4-wk delay in planting at Pullman, WA (about 47 °N lat), from an early September date and at Bushland, TX (35 °N lat), from a mid-October date reduced grain yields by 6% per wk (Thill et al., 1978; Musick & Dusek, 1980). For spring-wheat grown at Prosser, WA, a delay in planting from early March to mid-April reduced yields by 4% per wk (Nelson & Roberts, 1961). Delayed planting of spring wheat reduced yields by 7% per wk at Sidney, MT, and by 7.7% per wk at Logan, UT, when irrigation was adequate for high yields (Sharratt et al., 1980). These results indicate a 4 to 7% per wk yield reduction reported by Fischer (1981b) for delayed planting past the optimum date can be applied across a wide range in latitudes.

A line source sprinkler irrigation system was used in Utah to establish an ET range from about one-third of ET_{max} to ET_{max} for high yields. When seasonal ET was reduced to less than one-half of ET_{max}, planting date did not affect yields. The interaction of planting date response to water deficits indicates that the higher the yield level, the greater the yield loss from delayed planting. A 5-wk delay in planting (16 Apr.–21 May) reduced WUE from 1.14 to 0.61 kg/m^3 and IWUE from 0.94 to 0.60 kg/m^3. These results by Sharratt et al. (1980) indicate that delayed planting that reduces yields also reduces WUE.

Fall planting of spring wheat has expanded into the lower latitudes, and optimum planting dates for cultivars are important for optimizing anthesis dates to benefit from increasing solar radiation (day length) during grain filling while limiting the adverse effect of increasing temperatures (Fischer, 1985b). Climatic environmental optimization of planting dates can be addressed by a computer simulation model, as discussed by Fischer (1985b), where climatic data for a representative range of seasons can be used to estimate yield probabilities for a sequence of planting dates.

B. Row Spacing and Planting Rates

Irrigated wheat is planted in rows spaced 0.15 to 0.25 m, while dryland wheat in semiarid environments is planted in rows spaced 0.25 to 0.35 m. Wheat has relatively short leaves and lateral root extension, which necessitates the use of narrow rows for efficient absorption of solar radiaiton and soil water resources. When grown under high yield potentials, narrow row spacing increases yields (Joseph et al., 1985).

Under sprinkler irrigation, wheat is planted into a relatively smooth surface soil (without bed-furrows). Under surface irrigation with grades less than about 1%, the common irrigation practice in the Great Plains is to use beds and furrows, with furrows having relatively large flow capacities to irrigate field lengths of 400 to 800 m. A common bed-furrow spacing is 1 m (spacings of 0.75 and 1.5 m are less common) with planting in the direction of the bed-furrows. With 1-m bed-furrow spacing, four 0.25- or five 0.2-m-spaced rows are planted on each bed-furrow with single or double disk opener drills. With the single disk drills, the disks are set facing the bed to maintain existing bed-furrows during the planting operation.

On steeper sloping soils where small flow rates are applied to small furrows (rills or corrugations) to minimize erosion by irrigation water, furrows are spaced closer, mostly 0.5 to 0.75 m. In the USA, large planting units are used on smooth surface soils and small irrigation furrows are installed after planting. Furrow placement after planting reduces plant density (Nelson & Roberts, 1961) and delays canopy closure over the small furrows. This practice is more common in the northwestern states where surface-irrigated soils have greater slopes and more erosive textures. In the southwestern states, a common practice is to surface irrigate leveled blocks of about 5 to 20 ha that are either planted flat or on relatively large bed-furrows. Having bed-furrows can improve the uniformity distribution of irrigation water. However, planting of spring wheat in furrows can slow plant development and delay maturity and harvest. In this region of dry summers, delayed harvest is not a weather-related problem.

Planting rates for irrigated winter wheat are mostly in the range of 60 to 100 kg/ha, plant densities are mostly 120 to 200 per m^2, and head densities are mostly 500 to 800 per m^2. With reduced tillering associated with genotype or environment, planting rates are substantially increased and densities can exceed 300 per m^2. Spring wheats produce proportionately less grain on tiller heads than winter wheat, and seeding rates are normally about 50% higher (Reitz, 1976), while head densities tend to be 20 to 30% lower.

The compensation of tillering can result in similar grain yields over a relatively wide range in planting rates (Nelson & Roberts, 1963; Hooker et al., 1983; Shipley & Regier, 1972b; Joseph et al., 1985); however, higher planting rates normally increase vegetative growth and are more important for grazing (Shipley & Regier, 1972a). Higher plant densities also increase lodging potential (Nelson & Roberts, 1963). However, high plant densities may be needed for yield potential of late-planted winter wheat that fails to tiller in the fall and develops limited tillering during renewed growth in late winter before new tiller cessation after FI. Low planting rates combined with limited fall tillering can reduce yields. Asrar and Kanemasu (1985) found that reducing planting rate from 67 to 24 kg/ha for two wheat cultivars planted on a normal date for Manhattan, KS (3 October), reduced average LAI after jointing by 20%, grain yields by 27%, seasonal ET by 17%, and WUE by 9%.

Tiller senescence is accelerated by preanthesis soil-water deficits, and the sensitivity of planting rates to water deficits is relatively low. Because water deficits cause adjustments in tillers that produce heads and also in grain numbers per head, planting rates may not need adjusting for a range in irrigation water levels. Uniculm cultivars require higher planting rates and plant densities for adequate head densities since heads per plant may not appreciably exceed 1.0.

C. Grazing

On irrigated land, animal grazing of winter wheat forage is normally a planned management strategy that involves early planting and increased application of water and fertilizer. In the central and southern High Plains (Kansas, Oklahoma, northwest Texas, and small areas in eastern Colorado and New Mexico), winter wheat is managed for both grazing by stocker cattle and for grain production, with the grazing period beginning in November and terminating in February or March. Wheat that is planted on the optimum dates for grain production produces limited vegetative growth during GS1 and can support only moderate grazing.

Various aspects of wheat pasture grazing were reviewed in the *Proceedings of the National Wheat Pasture Symposium* (Horn, 1984), and wheat forage and grazing have been discussed in earlier state experiment station bulletins (Anderson, 1956; Holt et al., 1969; Malm et al., 1973). Because of winter dormancy and the limited spring growing period before the need for cattle removal for grain production, the major vegetative growth period that produces forage for grazing occurs in the fall. When winter wheat is grown for both forage and grain production, it is planted about 3 to 6 wk earlier than the optimum time for grain production. This earlier planting allows increased forage production but increases the need for fall irrigation. One additional surface irrigation is usually required for sustaining the longer period of fall growth.

During the longer warm fall growing period, winter wheat plants grow vegetatively (without stems) during GS1 to the 0.2- to 0.3-m height, main culm and tiller density increases to 2000 to 3000/m^2, and 2 to 4 Mg/ha of dry forage is produced. Growth mostly stops when mean air temperatures drop below 4 °C, normally in early December (Winter & Thompson, 1987).

In the central and southern Great Plains, irrigated wheat planted for grazing and grain production usually begins seasonal growth in early September with a wet soil. The first seasonal irrigation is normally applied by late October prior to the beginning of the grazing period in early November. Wheat is mostly grown on the fine-textured soils having relatively high water-storage capacity. When wheat is planted near the optimum date for grain production only, the fall irrigation is normally not applied. Thus, wheat managed for grazing plus grain production requires about one additional surface irrigation of about 100 mm, and the longer growing season increases seasonal ET by a proportional amount. October is the transition rainfall period to the dry winter months; in some years, the fall irrigation can be important for nodal root growth and anchoring the plant prior to beginning the grazing period.

Winter and Thompson (1987) found the need to remove cattle by the beginning of spring growth (before FI) to avoid yield reductions in high-yielding cultivars (4–6 Mg/ha). This work has emphasized the importance of limiting the duration of forage removal to GS1. As wheat develops during GS2, the increases in leaf area and biomass are important for grain yield potential; grazing harvest is probably a direct tradeoff with loss of grain yield potential. In earlier work with older cultivars, when irrigated wheat was managed for 3- to 4-Mg/ha grain yields, cattle grazing was allowed to continue for about 3 to 4 wk of renewed vegetative growth and removed prior to the extension of the developing head above the soil surface when primary culms were subject to removal by cattle (Reitz, 1976). The dry matter produced during 3 to 4 wk of slow, early spring growth following winter dormancy constitutes only about 10% of the grazing dry matter normally produced during the 8 to 10 wk of more rapid fall growth.

Where management and environmental conditions combine to produce excessive LAI and biomass during fall growth, fall grazing may be desirable to prevent yield reductions from overwinter lodging of lush growth and abortive loss of lodged culms. Shipley and Regier (1972a) found that early planted nongrazed wheat yielded 28% less than wheat planted on the same date and grazed from 12 November to 20 March. Severe grazing that results in almost complete removal of green leaf area of primary culms can result in overwinter abortive loss of primary culms and reduced grain yields produced on secondary culms. Moderate grazing of early planted wheat in the absence of disease problems with grazing termination near the end of GS1 results in normal or only slightly reduced grain yields compared with planting on an optimum date for grain production only.

VII. SUMMARY

Wheat ranks third in irrigated crop area in the USA (after corn and alfalfa), with average yields in 1984 of 4.6 Mg/ha. Adequate irrigation for high yields is mostly practiced in arid regions, while limited irrigation is widely practiced in semiarid climates where the crop is also grown without irrigation.

Wheat has excellent drought resistance and falls in the crop category of "drought tolerant with low water potential" (Turner, 1986). In field environments where stress develops slowly, cultivars have shown marked ability for osmotic adjustment to water deficits and rapid recovery following irrigation. Wheat has an extensive root system that permits rooting depth to exceed 1.0 m for spring wheats and 1.5 m for winter wheats in favorable rooting environments. It has a wide range of allowable water deficits for scheduling irrigations for efficient water use.

Irrigation tests, conducted in a wide range of climatic environments, indicated a yield range under adequate irrigation of mostly 4 to 8 Mg/ha, seasonal ET of about 350 to 700 mm, peak daily ET during grain filling of 3 to 9 mm/d, and seasonal WUE of 0.8 to 1.6 kg/m^3. Water-use efficiency of applied irrigation is largely similar to seasonal WUE except when reduced by application losses and nondepleted profile storage.

Wheat is only moderately sensitive to critical-stage plant water deficits compared with many other field crops. Deficits are normally the most sensitive during a period of about 10 to 20 d preceding and continuing through anthesis that reduces grain numbers per m^2. Development during grain filling is normally less sensitive, perhaps associated with plant ability to relocate preanthesis assimilate to filling grain as late-season water stress reduces photosynthesis. The preanthesis stress sensitivity is related to deficit effects on reduced biomass accumulation (head weight in particular) that reduce grain numbers per m^2. Crown root initiation and tillering, as well as jointing, have been reported as most critical for spring wheat in dry environments of sandy soil and appreciable evaporative demand and are probably associated with limited early-stage rooting for water extraction. Grain filling has been reported as critical in climates that experience periods of hot, dry winds—particularly during milk stage—that cause grain shrivelling.

Harvest index is mostly in the range 0.38 to 0.50 for high-yielding irrigated cultivars. During preanthesis, potential grain numbers are adjusted to biomass accumulation, and HI is affected little by water deficits. Once grain numbers become fixed, HI becomes sensitive to water deficits during grain filling.

Evapotranspiration-yield relationships indicate a threshold of about 0.2 ET_{max} for the first grain increment. Evapotranspiration-yield relationships are mostly linear over a wide range of water deficits, while WUE relationships are curvilinear. Yield relationships to applied irrigation are mostly curvilinear, diminishing-return functions. Similar response functions for applied N permit optimization analysis of marginal return inputs of water and N.

Although ET-yield relationships are mostly linear, they can become curvilinear when irrigation timing results in one or more applications that fail to increase yields and when profile drainage may be included in ET calculations at the high application levels. In the winter wheat region of the Great Plains, irrigation during early vegetative growth may increase straw more than grain yields. Also, increasing frequency of spring rainfall frequently limits yield response to irrigation during grain filling, thus reducing IWUE.

Wheat can be planted over a wide range of dates. However, a delay past the optimum period reduced irrigated yields by 4 to 7% per wk over a wide range of latitudes. Early planting is important for producing early-season forage for grazing by cattle in the central and southern Great Plains. For irrigated wheat managed for both grazing and grain production, early termination of grazing (before GS2) is more critical when managed for high yields. Nitrogen fertility is increasingly important for irrigated wheat managed for high yields and acceptable grain quality.

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